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Electron transport in InAs/AlGaSb ballistic rectifiers

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Abstract. Nonlinear transport properties of a ballistic rectifier fabricated from InAs/AlGaSb heterostructures are reported. The operation of the ballistic rectifier is based on the guidance of carriers by a square anti-dot structure. The structure was defined by electron beam lithography and wet chemical etching. The DC characteristics and magneto-transport properties of the ballistic rectifier have been measured at 77 K and 4.2 K. Rectification effects relying on the ballistic transport were observed. From the four-terminal resistance measured at low magnetic fields, we also observed magneto-resistance fluctuations corresponding to the electron trajectories and symmetry-breaking electron scattering, which are influenced by the magnetic field strength.

1. Introduction

Ballistic transport and nonlinear transport phenomena have been reported in semiconductor mesoscopic structures. The ballistic device structures mostly based on GaAs/AlGaAs heterostructures have been extensively studied. As a typical example of the application using these heterostructures, ballistic rectifier is a subject of active current investigation. In particular, these rectifiers are practical devices that can be used evaluate electron transport properties [1]-[4]. Based on the research of Song *et al*. [5]-[7], there were thought that ballistic rectification can be described by quasi-classical transport properties. The ballistic rectifiers were studied in the nonlinear regime, where ballistic electrons tend to travel in straight rather than curved paths. InAs/AlGaSb heterostructures offer promising new device applications due both to ballistic electron transport [8] and to the unique band alignment of this Type-II staggered and broken gap system. Low-dimensional electrons in InAs/AlGaSb heterostructures are attracting in the interests of the low effective mass, higher conduction band off-set and subsequent strong confinement in the heterostructure. Because of the strongly confined nature and low effective mass of the electrons in InAs, ballistic electron transport, quantum effect and rectification effects are expected to be observed at relatively high temperatures. In fact, the quantized conductance of ballistic constrictions using an InAs heterostructure has been observed at temperatures as high as 77 K [9]. In this paper, we describe the fabrication and characterization at 77 K and 4.2 K of an InAs/AlGaSb rectifier that can be used for the experimental investigations of the ballistic electrons in the heterostructure. We show that ballistic rectification occurs at the higher temperature and the heterostructure is very effective to produce ballistic rectifiers.

2. Fabrication of ballistic rectifier

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Ballistic rectifiers were fabricated from InAs/AlGaSb heterostructures grown on an undoped GaAs substrate by molecular beam epitaxy. In order to improve the crystal quality of the InAs channel layer, an undoped 1.5 μm thick AlSb layer was grown as a buffer layer to accommodate the lattice mismatch of about 7% between GaAs and InAs. The epitaxial layers on the substrate consist of a 1.5 μm-thick GaSb buffer, 200 nm-thick AlGaSb bottom barrier layer, 8 nm-thick AlSb, 15 nm-thick InAs channel layer, a 15 nm-thick AlGaSb upper barrier layer and a 10 nm-thick GaSb cap layer. From Hall-effect measurements by the van der Pauw method, a wafer showed electron mobility of 24,900 cm^2/Vs, sheet carrier density of 1.46×10^{12} cm^{-2} at 300 K, 145,700 cm^2/Vs and 8.46×10^{11} cm^{-2} at 77 K, 170,300 cm^2/Vs and 7.71×10^{11} cm^{-2} at 4.2 K, respectively. The mean free path of electrons corresponds to 2.5 μm at 4.2 K, which is longer than the distance from an exit of the source and drain to the square anti-dot. The anti-dot was defined with electron beam lithography and etched 70 nm deep by wet chemical etching. In/Au non-alloy ohmic contacts were deposited directly onto InAs channel by thermal evaporation and a lift-off process.

Figure 1 shows atomic force microscope images of the central part of the fabricated ballistic rectifier. The operation of the ballistic rectifier is based on the guidance of carriers by a square anti-dot structure, which is shown in Fig.1. The square anti-dot has a side-length and a height of about 1 μm. The wire width and wire length of the connected quantum wires are 350 nm and 2.1 μm, respectively. Independent of current direction, electrons ejected out of the narrow channels (source (*S*) and drain (*D*)) will be reflected from the edges of the anti-dot towards the lower (*L*) contact. As a result, an output voltage V_{LU} is induced between the *L* and the upper contact (*U*) even though an input current is reversed, and there is no polar change of the V_{LU}. Thus we expect to measure V_{LU} as a dc voltage for such a sample.

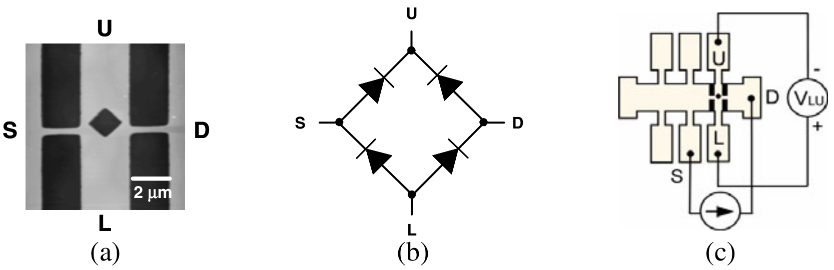

Figure1 (a) Atomic microscope image of an InAs ballistic rectifier. The dark areas are etched down through the two-dimensional electron gas layer. There are four electrical contacts; source (*S*), drain (*D*), lower (*L*), and upper (*U*). (b) The device operates similarly to a bridge rectifier based on a completely asymmetric structure [5]. (c) Measurement configuration.

3. Results and discussion

The DC characteristics of the fabricated InAs rectifiers have been investigated by sample current (I_{DS}) versus voltage (V_{LU}) measurements. Experiments were performed by applying a dc voltage (V_{DS}) between the source and drain, and measuring the dc output voltage V_{LU} between the lower and upper contact. Figure 2 shows the I_{DS}-V_{LU} characteristics of the ballistic rectifier at 77 K and 4.2 K. Rectification effects relying on the ballistic transport were observed at 77 K. The V_{LU} was generated between lower and upper contact of the devices; V_{LU} shows a negative polarity regardless of the I_{DS} polarity. Nonlinear characteristics and stronger rectification were observed at 4.2 K. However, the shape of the I-V curve was asymmetric, which we attribute to the unintentional breaking of the desired symmetry along the *L-U* axis from imperfections introduced during device fabrication.

Figure 3 shows a logarithmic plot of the I_{DS}-V_{LU} characteristics measured at 77 K and 4.2 K. The absolute voltage $|V_{LU}|$, which is averaged over both polarities shows nonlinear characteristics due to the rectification effect while I_{DS}-V_{DS} follow Ohm's law. Compared to the GaAs/AlGaAs rectifier

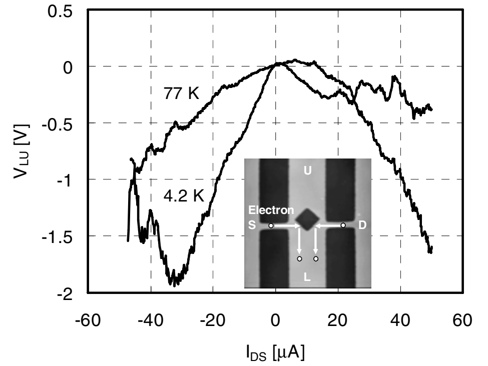

Figure2 DC characteristics measured at 77 K and 4.2 K. Arrows in the inset indicate typical trajectories of electrons through the *S* and *D* contact. The observed nonlinear characteristic is interpreted as originating from electrons being ejected through *S* and *D* and deflected by electron scattering which results in a negative voltage.

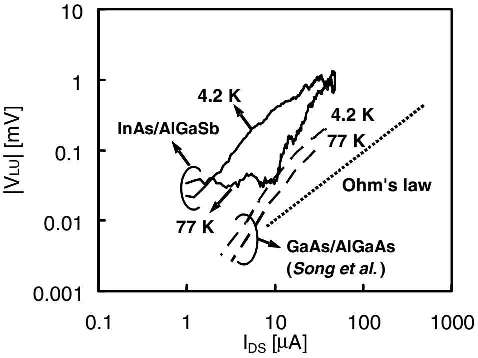

Figure3 Logarithmic plot of the I_{DS}-V_{LU} characteristics shown in Fig. 2. The absolute voltage $|V_{LU}|$ is averaged over both polarities.

reported by Song *et al.* [5], the nonlinear effect in InAs persists to higher values of I_{DS} well above 10 μA indicating the superiority of InAs. Clear rectification behaviour also has been observed at 4.2 K for the device. The rectification effects gradually decreased for $I_{DS} > 30$ μA. The sample current ranged as high as 50 μA much higher than that obtained with GaAs, and rectification was possible over this range. It is likely that increasing the sample current produced an enhanced anti-collimation effect, resulting in an increased propagation toward the *U* probe [10]. To develop a rectification effect, it is necessary for electrons propagating ballistically along the very narrow quantum wire to be scattered into the voltage probe (*L*).

In order to investigate magneto-transport in the InAs rectifier, the magnetoresistance has been measured at 4.2 K for a sample current of 1 μA. Figure 4 shows the magnetoresistance fluctuations. The data are subtracted from the zero field magnetoresistance. The magnetoresistance was measured by using two different configurations as shown in Fig.4 (b). We briefly discuss here the four-terminal resistance measured by configuration 1. In this configuration, Shubnikov-de Hass oscillations have been observed at higher magnetic fields above ± 1 T. At zero magnetic fields, electrons are driven between the source (*S*) and the voltage probe (*L*) by strong rectification effects (trajectory B_0).

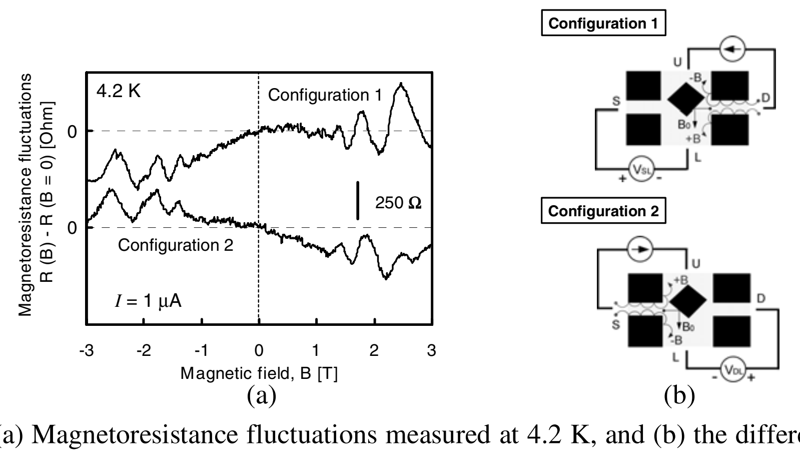

Figure4 (a) Magnetoresistance fluctuations measured at 4.2 K, and (b) the different measurement configurations. The typical some trajectories B_0, +*B*, and -*B* are shown in Fig.4 (b).

The magnetoresistance fluctuations shown in Fig. 4(a) should be constant in order to direct the electron trajectories towards the voltage probe *L*. On the other hand, when negative magnetic fields were applied, the resistance measured in this geometry was negative bending the electron towards probe *U* (trajectories -*B*). In configuration 2, the electron trajectories correspond to an interchanged distribution of an electron injector. As a result, the magnetoresistance decreased and eventually become negative with increasing positive magnetic fields. A four-terminal resistance formula derived within the theoretical work of the Landauer-Büttiker formula [11] [12] relates the Hall resistance to the contact resistance of the injector and collector. Similar to the Onsager-Casimir relations of the resistivity [13], a reciprocity symmetry relation of the four-terminal resistance exists,

$$R_{ij,kl}(B) = R_{kl,ij}(-B) \quad , \tag{1}$$

based on time-reversal symmetry in the presence of magnetic flux. The clear nonlinear effects observed in our experiment are described by Eq. (1). This implies that the specially-designed device geometry and the measurement configuration used in our experiments were particularly sensitive to nonlinear effects.

4. Conclusion

We have fabricated and characterized an InAs mesoscopic ballistic rectifier with a square anti-dot structure. Rectification characteristics were observed at 77 K and 4.2 K, and the magneto-transport properties were characterized by the consideration of classical electron trajectories. These results reveal a potential for higher temperature operation of a ballistic rectifier through the use of InAs/AlGaSb heterostructures.

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